All-SiC telescope technology at EADS-Astrium

Big step forward for space optical payloads

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***Abstract*—Ceramic mirrors and structures have become extremely attractive for high precision light weighted opto-mechanical applications. Developments over the past years by Boostec and EADS-Astrium have demonstrated the feasibility and versatility of the Sintered SiC material for numerous applications. The incomparable properties of the Boostec® Silicon Carbide material combined with more than 20 years efforts to develop a large range of joining processes, allows for large size light weighed space applications and systems. In the framework of earth and scientific observation, high and very high-resolution optical payloads have been developed by EADS-Astrium and its partner Boostec. Since the beginning of this new century, seven SiC instruments have been launched; they are successfully operating in space. More than ten instruments are under development, most of them being already tested and qualified. It means the manufacturing and testing of more than 150 SiC mirrors and structural parts for space applications under environmental conditions varying from 300 K to a few Kelvin. This unique experience acquired by EADS-Astrium and its partner allows now to propose the Boostec® SiC technology for the benefit of a large and complete range of space-based system for optical observation.**

***Index Terms*—Ceramic, Sintered Silicon Carbide, large optical payloads, lightweight mirrors and structures.**

I. Introduction

Over the past twenty years EADS-Astrium has developed the Sintered Silicon Carbide (S-SiC) technology for Space Applications in collaboration with a ceramic manufacturer: Boostec company (Tarbes, France). Its unique thermo-mechanical properties, associated with its polishing capability, make S-SiC an ideal material for building ultra-stable lightweight space based telescopes or mirrors. S-SiC is a cost effective alternative to Beryllium and the ultra-lightweight ULE/Zerodur technologies. In complement to the material manufacturing process, EADS-Astrium has developed several assembly techniques (bolting, brazing, bonding,…) to manufacture large and complex SiC assemblies[2].

Nowadays, the necessity to always go further in the exploration of the Space requires the observation instruments sent in the Space to continuously improve their performances. Thus, the optics needs to be larger and larger to achieve higher spatial resolution, accuracy or light flux collection when observing Earth or the Universe. That is why, it was mandatory to find and develop materials with very good optical, thermo-mechanical, and lightweight properties such as Silicon Carbide to meet ambitious mission requirements.

Recent EADS-Astrium developments have shown the growth potential of the SiC technology. If originally S-SiC applications were limited to small size instruments and mirrors, recent payload developments, have allowed demonstrating the ability of this technology to achieve the more and more demanding performances for the on-going and future programs. SiC manufacturing processes and manufacturing facilities, at Boostec premises, have also evolved to comply with the current and future very large space instrument and mirrors needs. They are currently able to produce mirrors and structures up to 3.8 meters diameter, i.e. close to the limitation provided by the largest launcher fairings

S-SiC has become a new generation space material. This paper provides an overview of the S-SiC properties, its manufacturing processes for mirrors and structures, and its application on space optical payloads.

II. BOOSTEC® SIC KEY PROPERTIES

Sintered SiC mechanical and thermal properties presented in the Figure 1 highlight its high stiffness and its high thermo-mechanical stability. S-SiC provides a number of technical advantages, as a result of superior material properties.

Boostec® SiC has outstanding properties. The main features and advantages of SiC are as follows:

- A fundamental reason for the success obtained with Boostec S-SiC material is that the material is extremely homogeneous, featuring very low in-built stresses and a single-phase crystalline microstructure. Performances reproducibility from batch to batch secures the development of space instruments. S-SiC has also isotropic properties (Isotropic characteristics of CTE, thermal conductivity and mechanical properties) facilitating optical payloads dimensioning and behavioral prediction. This is in a large part due to the fine grained SiC powder used and cold isostatic pressing (CIP) technique; the combination of both gives a higher degree of homogeneity and isotropy than obtained in other competing types of SiC; furthermore, after sintering, the density is close to that of pure SiC. Contrary to reaction bonded SiC, no secondary operations are required such as high temperature silicon infiltration (that can result in an anisotropic and an inhomogeneous material) or sand-blasting for surface molten SiC removal (that can introduce surface defects).

- Its low specific density (< 3.2 g/cm³) associated to a very high stiffness (420 GPa) and a high bending strength (>350 MPa) allows stiff, very lightweight optical systems to be produced. It also makes simple the zero-g testing.
- Its low coefficient of thermal expansion (CTE: 2.2 x 10^{-6}K-1 at room temperature and near zero below 100K) combined with a very high thermal conductivity (~ 180W/m.K) and high thermal capacitance (Cp > 650 J/kg.K) allows visible quality imaging in the presence of stressing, and changing thermal loads condition. This makes it a reference material to achieve the stringent thermo-elastic performances of space optical payloads over a broad operating temperature range from a few K (cryogenic) to 300 K or even higher for high energy applications (~1800K) unlike composites and glass. Passive a-thermal systems have been produced, demonstrating the ability of the material to provide high quality imaging, without the need of actively controlled focus adjust mechanisms.
- Its stability over time: Insensitive to space radiations (no degradation for 200Mrad Gamma rays), no aging or creep deformation under stress, no moisture sensitivity, no outgassing, no residual stresses, high fatigue, corrosion and abrasion resistance making it reliable for long term space mission and allowing rapid on-orbit data acquisition.

		S-SiC Boostec	**Béryllium** Brushwellman	**Zerodur** class 0 Schott	**HB CeSiC** ECM-Melco	**Si3N4** FCT	**Aluminium** Alloy 6061
Young modulus: E	**GPa**	**420**	287	92	350	300	70
Density: ρ	**kg/dm³**	3,2	**1,9**	2,6	3,0	3,3	2,7
CTE: α.10-6	**m/m-K**	2,2	11,3	**0,02**	2,3	1,0	23,0
Thermal conductivity: λ	**W/m-K**	**180**	**216**	2	145	25	167
Specific heat : Cp	**J/kg-K**	680	**1900**	810	710	[710]	900
Specific rigidity : E/ρ		**131**	**155**	36	118	92	26
Thermal steady state : λ/α		**82**	19	80	63	25	7
Thermal diffusivity : λ/(ρ xCp)	**x 1000**	**83**	61	1	69	11	69
Thermal transient: λ/(αxρ xCp)	**x 1000**	**38**	5	38	30	11	3

Fig. 1. Space Telescopes materials: S-SiC properties compared to conventional materials

Good mechanical properties & excellent homogeneity make S-SiC a material of choice for high stable structures and mirrors[1]. The material's most advantageous features for ground-based and space-based opto-mechanical mirrors and instruments are the combination of high Specific stiffness (E/ρ), with high thermal distortion ratio (λ/α)and high thermal diffusivity.

III. RECALL OF MANUFACTURING PROCESS

Silicon Carbide (SiC) is a compound of Silicon and Carbon. It is obtained from the chemical reaction between silica sand and coke carbon at very high temperature. Nowadays, SiC is industrially manufactured for many applications. The major manufacturing steps of a Sintered SiC blank are recalled below.

Boostec® SiC raw material is a premix of fine SiC powder (< 1 µm grain size), sintering additives and temporary binders. This material is isostatically pressed (pressure > 1400 bars) at room temperature into a machinable blank. The so called green body shows quite no internal stress.

This green body is then machined with the help of high speed CNC milling machines. This near-net-shape manufacturing process allows complex, light-weighted optical and structural elements to be produced with very little post-machining. During the last ten years, BOOSTEC has continuously improved the reliability and also the speed of its process. Software for programming the CNC milling machines and also to verify the machining programs has been invested, allowing the green machining of very complex 3D shapes. It therefore provides significant schedule advantages compared to the state-of-the-art for low expansion glass-ceramics. These technical and manufacturing advantages become even more significant as the payload aperture increases, and/or as the number of units increases. S-SiC is uniquely well suited to address future needs associated to very large space applications.

Then the machined green body is pressure-less sintered at about 2000 °C under protective atmosphere. Organic binders are removed during sintering process and the material is made of > 98.5% SiC. This is the reason why S-SiC properties are very homogeneous thus enabling both a good size control and an easy polishing. The sintering gives an isotropic shrinkage of SiC parts. Nevertheless, the uncertainty on the size of the sintered component remains below 0.4%.

When deemed necessary, fine grinding, optionally lapping the interfaces or polishing the optical faces is performed after sintering phase.

Mechanical proof-testing, final check and cleaning is performed prior S-SiC part delivery.

To achieve the development of the Herschel telescope, Boostec has enlarged and validated S-SiC manufacturing facilities, from the SiC powder preparation up to the final grinding. Therefore, processes and facilities are now fully qualified to produce quasi-monolithic SiC pieces as large as 3.8m diameter.

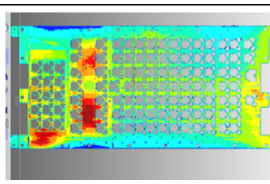
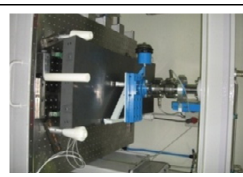
	
SiC Powder preparation.	Isostatic pressing: In the cold isostatic press, the raw material is very homogeneously compacted with help of a high-pressure liquid, through a rubber bag
	
Milling machine for Green blank machining: A near net shaping process makes very cost effective manufacturing	Sintering oven: under a non-oxidizing atmosphere, the SiC is sintered at ~2000°C
	
Grinding machine: when accurate geometry or size is required, areas of the sintered pieces are ground	Brazing oven : performed at about 1400°C, allow the brazing of piece up to ∅ 4 3.8 m
	
Size or geometry control: with help of laser tracker or CMCs 3D scanner	Mechanical proof test (static) followed by a Non Destructive Inspection

Fig. 2. S-SiC manufacturing process

The recent development of the GAIA Payload Module and Sentinel 2 MSI has allowed making a significant breakthrough in the machining of S-SiC parts [14]. Nowadays Boostec manufacturing facilities make possible manufacturing very large Sintered SiC parts having complex shape and high light-weighting ratio as illustrated in next figure.

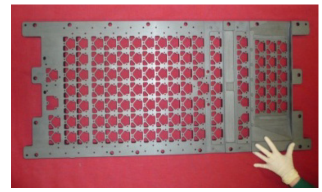
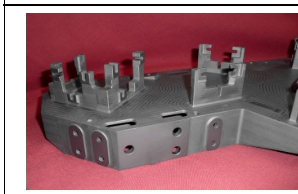
	
Sentinel-2 MSI telescope structure	GAIA Folder Optical Structure (FOS)
	
GAIA Torus segment	GAIA detector baseplate: 1.15m x 0.53 m
	
GAIA Torus segment	Sentinel-2 MSI primary mirror: mushroom fixation concept
	
GAIA BAM: detail of the monolithic interferometry optical bench	GAIA monolithic Focal Plane cold radiator: 1.17m x 0.62 m x 0.41 m

Fig. 3. Examples of large light-weighted and complex shape S-SiC parts

The Boostec® SiC can be easily polished as it is single phased (polishing convergence as good as for glass). The material can therefore be used for optics in the visible range. It can be metal coated by using the same process than for silica glass and with similar performances. Several types of reflecting coating have been space qualified on the sintered SiC (Al, Ag, Au).

The pressure-less sintering of SiC gives a densification level over 98%, then, the raw sintered SiC exhibits a residual porosity of typically 2% in volume, therefore in surface. It can generate, for some applications (e.g. astronomic observation), too much stray light level. That is the reason why, for these applications a SiC layer (CVD process) is applied on top of the optical surface, which thickness can vary from a few tens µm to about 1 mm, depending on the final application.

This SiC layer allows reaching roughness down to 0.1 nm. Thanks to its high purity, the S-SiC coefficient of thermal expansion (CTE) fits quite perfectly well with the one of the extremely pure CVD SiC.

After having SiC CVD coated the mirrors optical face, they are re-shaped by grinding in Boostec facilities thus recovering the previous < 50µm shape defect. The large off-axis GAIA mirrors have been successfully re-ground by this way.

For very large mirror, each individual segment is coated with CVD SiC. Then all segments are brazed together prior to being re-shaped by grinding and polishing.

The SiC CVD coating is also compatible with use of modern mirrors polishing technics such as ion-beam figuring (IBF) which significantly improve the rms surface roughness. Ion-beam polishing consists in bombarding the surface to be polished with an ion beam (usually a beam of Ar+) and allows fine erosion of the surface. The resulting surface is smoother.

IV. Joining techniques

Available facilities allow manufacturing monolithic S-SiC pieces sizing up to 1.7m x 1.2m. This covers most of the needs for space applications and manufacturing larger monolithic pieces would require significant industrial investments. Therefore, the cost effective and safe approach to manufacture larger S-SiC pieces, such as HERSCHEL primary reflector or GAIA torus , is to assemble together smaller pieces, which are well within available manufacturing capabilities. Furthermore joining techniques are absolutely necessary for telescope manufacturing where we have to integrate SiC mirror onto SiC mechanical structure, that is the reason why large development efforts have been spent in the last ten years to characterize and validate different assembly techniques. Through the several techniques that have been envisaged the following have been validated over a large temperature range and are baseline for flight space instruments.

A. Bolting technique

Mechanical assembly of two parts (SiC-SiC or SiC-metal junction) have been deeply characterized to allow a predictable behaviour of each assembly. A particular attention must be paid on the design, dimensioning, and assembly of a ceramic bolted joint, but this assembly technique offers a very efficient solution to obtain micrometrical stability performances. Thanks to the high S-SiC friction coefficient and to the possibility to get high interface flatness (through a quasi-polish process) excellent boundary conditions are obtained, thus making very stable interface joints.

B. Epoxy bonding

For this conventional assembly process, a large set of epoxy adhesives have been characterized over a wide temperature range, to determine achievable performances, such as strength and stability.

C. *Ceramic bonding*

With this technique, the assembly of SiC pieces is performed in a "green body" status, by means of ceramic cement [4]. Then they are bonded together during the sintering process. When sintering is achieved, a monolithic SiC part is obtained. Maximum dimensions of SiC pieces achievable with this process are mainly imposed by the sintering oven capacity. Current Boostec sintering oven capacity is about 1,7m x 1,2m.

D. High temperature brazing

SiC parts which exceed 1.7m x 1.2m in size are obtained by brazing the assembly of previously sintered and ground pieces.

The assembly of SiC pieces is performed while each SiC piece is already sintered. The Brazing technique consists in adding a silicon alloy between two sintered SiC pieces. The pieces to be brazed are maintained using specific tools during the process while the molten alloy fills in the gap between the SiC pieces by capillary action. Brazing operation is carried out at high temperature (~1400°C) under a non-oxiding atmosphere. The following great properties are obtained:

- The braze material CTE is matching with that of S-SiC, say within 0.1 ppm/K or so.
- The brazing joint can be very thin. For very thin joints (a few µm), the brazing strength is comparable or better than the S-SiC one.
- The brazing is non-reactive, i.e. the S-SiC material is not attacked.

The major advantages of this available brazing technique are that the sintering of elementary S-SiC pieces is easy and the brazing material does not introduce any distortion under temperature changes. Maximum size of SiC pieces achievable with this process is imposed by the brazing oven capacity. Current Boostec brazing oven capacity is compatible with a 3.8m diameter SiC part. This technique has been successfully used for producing very large space parts such as the Φ 3.5 m Herschel primary mirror, the Φ 1.5 m Aladin-Aeolus primary mirror, the 1.8 m x 1.4 m NIRSpec optical bench and the 3m diameter GAIA torus.

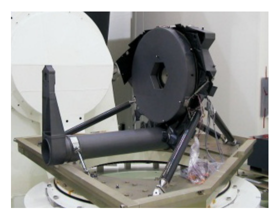
	
Bolting technique	Epoxy bonding
	
Ceramic bonding	Brazing

Fig. 4. Example of S-SiC joining techniques

V. Overview of Few Astrium Developments with BOOSTEC® SiC

Over the past 15 years the application of Sintered Silicon Carbide materials for space based optical payloads has been continuously expanding. The space community has long recognized the technical, cost, and schedule benefits associated with the material, and adoption of the technology is facilitated as more successful flight systems are demonstrated. Since the beginning of this new century, seven EADS-Astrium S-SiC instruments have been launched and are successfully operated in space. More than ten instruments are under development, most of them being already tested and qualified. It means that more than 150 SiC mirrors and structural parts have been manufactured and tested for space applications under environmental conditions varying from 300 K to a few Kelvin.

A. Rosetta Osiris payload

The Narrow Angle Camera of OSIRIS is a Three Mirror Anastigmat (TMA). It has been embarked on the ESA Rosetta satellite which is still flying towards the Comet 67 P/Churyumov-Gerasimenko. It has already made nice pictures of planets (Mars, the Earth,…) and also asteroids, taking profit from different flybys. Its aim is to take pictures of the comet during the mission from a distance that can get as close as 300 meters. As a long part of the mission is made at a large distance from the sun the available power is very low. Therefore, the key instrument design drivers were: very low mass, launch loads compatible with Ariane-5 and very low thermal power consumption (<5 W). Due to these constraints it was decided to manufacture an all S-SiC telescope: both structure and mirrors are made of S-SiC. Being a-thermal, this telescope does not need any thermal control as its behavior under large homogeneous temperature changes is perfectly homothetic and thus keeps the image focused onto the detector on all temperature range (telescope structure fluctuates freely between –100 and +70°C). The high thermal conductivity prevents from having temperature gradients.

The mirrors (using mushroom fixation concept) are directly bolted onto the structure. The wavefront error requirement for the final on orbit telescope is 63 nm rms.

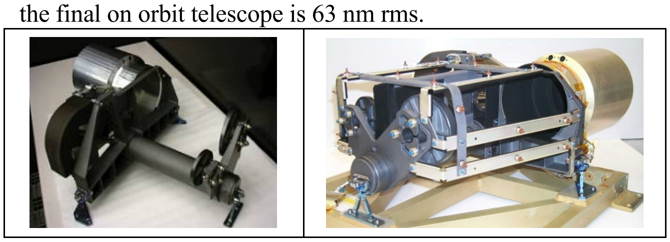


Fig. 5. Rosetta Osiris Narrow Angle Camera (NAC)

B. Herschel telescope

The Herschel satellite is part of Herschel/Planck program of the European Space Agency (ESA) devoted to far infrared astronomy [3], [12]. Herschel main goal is to study how the first stars and galaxies were formed and evolved. Herschel (Cassegrain type), the largest telescope in space, is undoubtedly the most challenging of them. Since June 2009, it has been successfully collecting the long wave-length radiation from some of the coldest and most distant objects in the Universe; it is clearly stated that its optical performances fully meet the scientists' expectations

The Herschel Space telescope operates at cryogenic temperature (~ 80 K) in the far infrared wavelength range (80 µm to 600 µm) and it uses S-SiC technology. It consists of a large very fast parabolic reflector (diameter 3.5 m, f/0.5) and a hyperbolic secondary reflector connected to the primary reflector by means of a metering structure. The whole telescope is isostatically mounted on the cryostat structure, inside which the science instruments are located. The Herschel telescope weights less than 300 kg while it would have been 1.5 tons with standard technology. The most complex element was obviously the ∅ 3.5 m primary reflector that is composed of 12 SiC segments brazed together. The segments are open-back light weighted with triangular cells. The rib heights and thickness are optimized for minimizing the mass while meeting frequency requirement. As an illustrative example, the rib height varies from 0,1 m in the center of the segment to a few mm at the edge. The thickness of the optical surface is lower than 3 mm. After having accurately ground its both edges, each sintered segment is accurately and iso-statically positioned with respect to the adjacent ones on a support tool compatible with the 1400°C temperature environment of the brazing oven. The aim is to guarantee the geometrical adjustments for the brazing process, and to define the relative positions, which minimize the final mass of the reflector, while keeping a final skin thickness higher than 2mm. The positioning error of each segment with respect to theoretical optical surface is less than 100µm; the gap between two adjacent segments remains below a few µm. Ultrasonic inspection, performed after the brazing sequence, has shown that all segments were perfectly brazed to each other. Longitudinal shift of segment front faces, after brazing, remains within a 100µm tolerance. The next manufacturing step of the mirror was the grinding operation of the optical surface. During this grinding operation, the reflector was maintained by the 3 bipods and by several supporting points that reduce potential distortions under the grinding efforts. After grinding the surface error was about 100 µm with respect to the best-fit parabola. Then, the mirror has been polished in Opteon premises in Turku (Finland) to lower the wave front error down to 3 µm rms and the surface roughness below 30 nm. The reflector was aluminum coated at Calar Alto Observatory facility with a thickness larger than 200 nm for ensuring a low emissivity (and a high reflectivity) at Herschel wavelengths.

Fig. 6. Herschel telescope

C. Aeolus Aladin telescope

The Aladin instrument (Aeolus mission), is a Doppler Wind Lidar based on a diode-pumped Nd-YAG laser and a direct detection receiver. The instrument is pointing at 35° across-track from the nadir in the measurement mode. The Cassegrain telescope is an a-focal telescope made of two parabolas.

The Aladin telescope functions are to transmit the laser beam along the requested line of sight referenced with respect to the star tracker reference frame and to collect the laser beam flux partially reflected by the atmosphere to deliver it to the optical bench.

The whole S-SiC telescope concept consists in a Φ1.5m parabolic primary reflector made of two half S-SiC circular segments brazed together diametrically. The secondary S-SiC mirror (Φ 46: convex parabola) is fixed by means a S-SiC tripod structure on the primary mirror (M1-M2 distance=1320mm). Each of the 3 struts of the tripod is constituted by two half S-SiC shells bonded together to achieve the required stiffness while minimizing the occultation ratio to keep it below 6.5% for emission, assuming a Gaussian flux distribution. The 3 legs are glue together, on topside, by means of S-SiC fittings. Fixation onto the primary mirror is achieved through 3 titanium end fittings that are bolted on M1 reflector through M10 titanium bolts. The thin part of the end fittings aims at providing a quasi iso-static fixation by releasing radial and tangential degrees of freedom. The whole S-SiC telescope assembly is fixed on top of the instrument carrying structure via 3 bipods, which also provide an iso-static interface.

The primary mirror is an open back structure (weight~50kg i.e. 28 kg/m2). The thickness of front face skin is 3 mm. The main rib network is organized in isosceles triangular cells to ensure the mirror required stiffness. The mirror sag is about 100 mm while the total mirror envelope thickness is 125 mm (rear face to front face edges). It has been polished on bare SiC.

The focus quality can thermally be adjusted by means of controlled heaters, thus making refocusing mechanism useless.

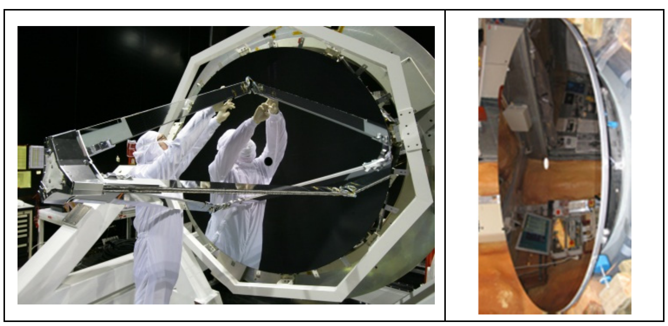


Fig. 7. Aeolus Aladin telescope and primary mirror

D. GAIA payload module

GAIA is the 6th cornerstone of the ESA scientific program. It will provide positional, photometric and radial velocity measurements of about one billion star of our galaxy, with an unprecedented accuracy[7],[11],[13]. It includes three science instruments that operate at a cryogenic operational temperature of 130K:

- The Astro which is devoted to the star angular position measurements (astrometry),
- The Blue & Red Photometers which provide continuous star spectra on 60 pixels in the band 330-1000 nm for astrophysics and Astro chromaticity calibration,
- The Radial Velocity Spectrometer (RVS) which provides high resolution spectra on 1260 pixels in the narrow band 847-874 nm and radial velocity measurements by Doppler Effect.

Two 1.5 m TMAs point towards two directions forming a “Basic Angle” of 106.5°. The beams are then recombined with help of two folding mirrors, thus allowing them sharing a single large focal plane. The astrometric accuracy (10-25 μarcsec at magnitude 15) relies on the very high stability of this “Basic Angle” (less than 10 μarcsec over 6 hours, i.e.: a coin of 2€ on moon observed from earth).

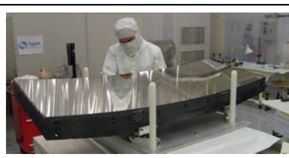
The S-SiC material appeared essential for obtaining the required mechanically and thermally ultra-stable payload. The mirrors, the main optical bench, the focal plane and also various subsystem structures are made of S-SiC.

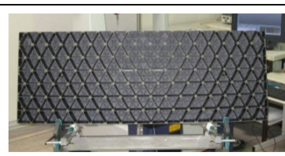
In total, the GAIA instrument will embark 284 S-SiC parts of 80 different types (106 of them are identical CCD supports). Among them, few were quite challenging, due to their large size and their highly complex shape. Namely:

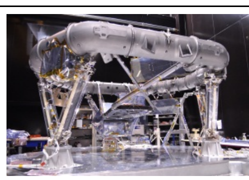
- The primary mirror (M1) as it is the largest one: 1.50 m x 0.56 m and have a very large offset corresponding to a master mirror of about 2.8m diameter. The process for manufacturing the blank and the one for polishing (by SAGEM-REOSC) have been previously validated through a scale one M1 demonstrator. Flight models were delivered with a WFE better than 20 nm RMS.
- The torus: The highly stiff and stable optical bench of the GAIA instrument is made of 17 segments forming the large ring plus 2 additional supports for M1 mirrors attachments forming a quasi-octagonal 3 m diameter structure. All segments have been joined by brazing technique, thus giving the required stiffness and stability. Each torus segment was very challenging part, due to their quite large size (0.5 - 1 m) and complex shapes. Furthermore, they provide a lot of interfaces for setting-up on the satellite but also for mounting all optics and the focal plane as well. Before brazing assembly, they have been grinded and lapped very accurately. Each segment has also been mechanically proof-tested. The brazing assembly was undoubtedly the key challenge of the torus development. The 19 S-SiC parts were located accurately until the end of the single brazing run. An ultrasound based technique has been developed specifically with the CEA (the French Nuclear Agency) for the verification all the brazed joints. It allowed the detection and the cartography of possible voids down to a few mm². No significant defects were found in the brazed joints.
- The focal plane: The 106 CCDs of GAIA are mounted on individual S-SiC substrates and then bolted on a

large alleviated S-SiC base-plate [6]. Beside the main Astro CCD plane, it features 3 other planes which are tilted with different angles. This base-plate is then fixed by ~20 bolt joints on the S-SiC Cold Radiator for stiffening and cooling purpose. The fixation planes of these two large S-SiC parts have been polished to a local flatness of 1 µm by WINLIGHT. The Cold Radiator includes 6 accurate interfaces areas which allow hanging it on the torus through 6 Glass Fiber Reinforced Polymer (GFRP) struts.

- The Basic Angle Monitoring (BAM): The extremely accurate "Basic Angle" is monitored with help of interferometry. For that purpose, the GAIA payload includes 2 optical S-SiC benches developed by TNO. The main part is a very lightweight base-plate (only 1 mm thick ribs) which includes a lot of brackets for mounting all the very stable optics. The BAM aims at measuring the stability of the angle between the two GAIA telescopes with accuracy better than 0.5 µarcsec over a 6 hours period duration. Over this period the shift between the optics remains stable below 1 picometer.
- The Radial Velocity Spectrometer (RVS), is located between the telescope exit pupil and the GAIA focal plane [15]. Its complex function is to compensate the off-axis aberrations of the two telescopes, to minimize distortion with the same focal length reference, for each dispersed wavelength, and to spread the spectrum of the stars in the IR bandwidth, from 847 to 874 nm. To comply with its mission, the RVS must feature the required wave front error (WFE), magnification and dispersion as well. To cope with mass and stiffness performances, The RVS structure is mainly made of S-SiC. The six different optical components of the RVS (2 prisms, 2 Féry prisms, one filter and one blazed diffraction grating) are made from selected fused silica material with a low thermal expansion similar to the one of the S-SiC material. Each optical element is isostatically mounted by 3 invar bipods in the S-SiC RVS primary structure. The RVS is bolted on the Folder Optical Structure (FOS) of the Payload structure.

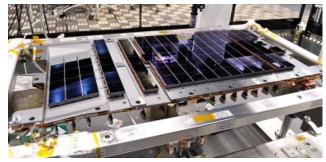

GAIA primary mirror

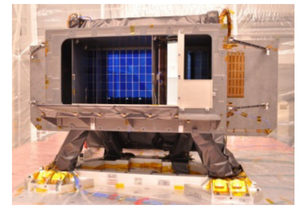

GAIA Primary mirror


GAIA torus


GAIA Torus

Fig. 8. GAIA payload structures and mirrors


GAIA Focal Plane


GAIA Focal Plane


GAIA Basic Angle Monitoring

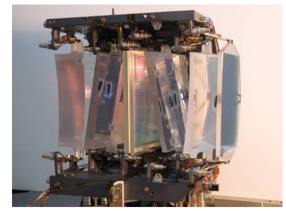

GAIA RVS

Fig. 9. GAIA payload module main assemblies

With less than 740 Kg (including 180 Kg of the 106 CCD's Focal Plane Assembly), GAIA PLM is a clear demonstration of the interest of Boostec® SiC for large space optical payloads (GAIA optical collecting area ~1.5 m²)

E. JWST NIRSPEC payload

JWST will be operated in a manner similar to the HST.
The ESA NIRSpec instrument on JWST is in many ways complementary to the NASA-funded JWST NIRCam near infrared camera. While NIRCam takes direct pictures of a patch of sky through the JWST telescope, NIRSpec is designed to measure the spectra of pre-selected objects contained in it. NIRSpec is a multi-object spectrograph, meaning that it is capable of measuring the spectra of up to 100 objects simultaneously[8].
The NIRSpec instrument operates at a temperature below 35K. It carries a total of six diffraction gratings and a prism as its dispersive elements. A noteworthy feature of NIRSpec is the use of sintered silicon carbide (S-SiC) ceramic as basic material for the three telescopes, the folding mirrors and the structural parts of the instrument. This material is very suitable for low temperature optical applications.


FORE optics TMA

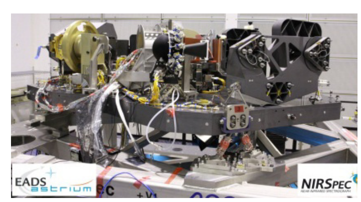

NIRSpec payload

Fig. 10. JWST NIRSpec payload

F. Sentinel 2 MSI payload

The Sentinel 2 Multi Spectral Instrument is a filter based push-broom imager. It provides imagery in 13 spectral channels with spatial resolutions ranging from 10m to 60 m. The instrument features an optical telescope providing a wide field of view to achieve the required swath width of 290 Km. An oblong pupil equivalent to 15 cm diameter, has been selected to achieve a compact design and optimized optical performance.

The instrument is required to operate over a wide spectral range extending from the Visible Near_Infra-Red (VNIR, 400-1100 nm) to the Short-Wave-Infra-Red (SWIR, 1100-2500 nm). The optical design of the instrument is based on a Three Mirror Anastigmat concept that corrects spherical aberration, coma and ana-stigmatism and features mirror dimensions up to 600 mm. In order to ensure the homogeneity of the filter spectral response, a tele-centric configuration has been chosen. The optical beam is split between VNIR channel (in reflection) and SWIR channel (in transmission) by a splitter close to the focal plane.

The 3 mirrors of the TMA telescope are made of S-SiC and supported by a S-SiC monolithic structure. This structure is connected to the platform top panel by 3 bipods performing an isostatic mounting. The main structure also supports the two separate S-SiC focal planes and the dichroic filter which splits the beam into two spectral domains.

The VNIR focal plane assembly accommodates 12 monolithic Silicon CMOS detectors, where 10 multispectral channels are combined on a single detector.

The SWIR focal plane assembly is based on 12 hybrid HgCdTe-CMOS technology, where 3 multi-spectral channels are integrated on a single detector. To achieve the radiometric performance, these detectors are passively cooled down to 190K.

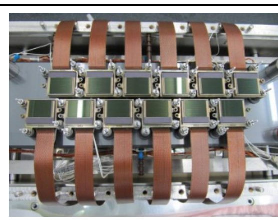
	
Telescope structure	Telescope assembly
	
SWIR focal plane structure and radiator	VNIR focal plane

Fig. 11. Sentinel 2 Multi Spectral Imager

G. Remote sensing payloads

EADS Astrium has successfully carried out several projects including all S-SiC telescopes which are now operating in space. This includes i) the Φ 600 mm Cassegrain telescope for Formosat-2 (operated by NSPO: Taiwan) [5], ii) the similar THEOS one (operated by GISTDA: Thailand) and iii) the GOCI TMA type telescope embarked onboard of the geostationary COMS satellite (operated by KARI: Korea)[10].

It has then developed a new product line of compact and versatile instruments for high resolution missions in Earth Observation [9]. First version has been developed in the frame of the ALSAT-2 contract awarded by the Algerian Space Agency (ASAL) to EADS Astrium. The Silicon Carbide Korsch-type telescope coupled with a multi-lines detector array offers a 2.5m GSD in PAN band at Nadir @ 680 km altitude (10 m GSD in the four multispectral bands) with a 17.5 km swath width. This compact camera – 340 (W) x 460 (L) x 510 (H) mm3, 13kg is embarked on a Myriade-type small platform. Two satellites are developed; the first one is already in flight.

Several other versions of the instrument have already been developed with enhanced resolution or/and larger field of view.

The optical assembly is based on a Korsch-type telescope including three aspheric mirrors and two folding mirrors. The camera is based on an all Silicon Carbide (SiC) telescope coupled with a compact focal plane unit.

The primary structure is composed of three main parts: a baseplate, a metering structure with a spider supporting the secondary mirror (M2), and the focal plane. The baseplate supports the M2 metering structure, the mirrors, the detector and its front-end electronics. All these parts are made of S-SiC. Thanks to high thermal conductivity, low coefficient of expansion and high stiffness of SiC material, this simple and efficient structure assembly provides excellent thermo-mechanical performances. During operational modes, only five lines are necessary for telescope thermal control and the mean power consumption is only 5 Watts.

Even if not yet used in orbit, a separate thermal control of a telescope mirror with respect to the telescope structure offers an efficient and reliable refocusing capacity for free.

Started more recently, the development of a ∅650mm instrument is on the right track. The integration of the front cavity has been performed; the focal plane assembly integration is on-going. It weights less than 160 Kg (including focal plane and video electronics), while a 220 – 250 kg instrument should have been obtained from standard technology. This makes S-SiC a very competitive technology.

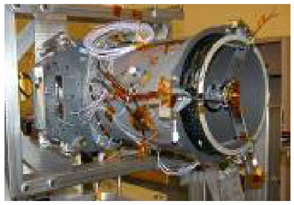
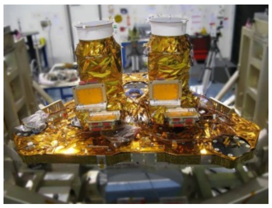
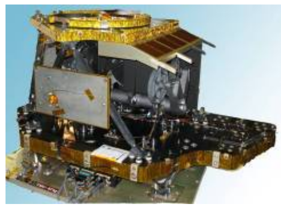
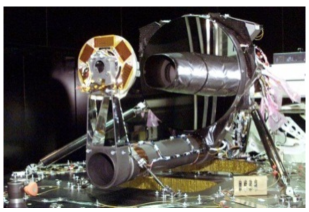
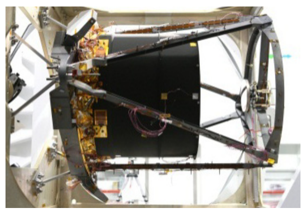
	
∅200 mm Korsh camera	∅200 mm Korsh camera
	
SPOT-6 & 7 Korsh cameras	COMS-GOCI optical payload
	
Formosat & Theos Cassegrin cameras	∅ 650 mm Korsh camera

Fig. 12. Overview of S-SiC remote sensing payloads

VI. Conclusion

After more than ten years of development and characterisation, Boostec® SiC material and relevant technology have now reached the level of maturity required for the development of large space mirrors, structures and focal plane hardware. This well-defined and cost efficient technology still presents a high growth potential; it has been successfully used for many demanding optical payloads. If the development of Herschel telescope has been a turning point for the S-SiC technology through the significant industrial and technical step it has enabled, Aladin telescope and GAIA, can be viewed as the first representatives of the new generation of large space borne telescopes for science or earth observation.

Sintered SiC has now become a very common material for large telescopes mirrors. Interest in S-SiC as an opto-mechanical material is continuously expanding as every year brings its new space flight successes. EADS-Astrium and Boostec are presently pushing up the technology in the aim of manufacturing ultra-light-weighted mirrors with area density down to 10 kg/m² for future very large instruments. Furthermore, the Sintered SiC manufacturing is really cost effective, thus making it a material of choice for future ground and space based telescopes.

Acknowledgment

The developments of the Herschel Telescope, Aeolus-Aladin, NIRSpec, Sentinel 2 MSI and GAIA are funded by the European Space Agency (ESA). EADS-Astrium and Boostec would like to thank the ESA projects teams for their support in these challenging programs and for having granted its confidence for the development of their programs. All the companies involved in the instrument development are gratefully acknowledged.

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